Double hot-embossing with polymeric intermediate mould

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Abstract

Our approach uses a two-step replication process for hot embossing and a rigid polymeric intermediate mould. This process overcomes some geometrical limitations in microstructured mould fabrication, enables positive-tone imprinting, prolongs the lifetime of the master, and lowers the overall cost of the replication process.

Keywords: hot-embossing, polymeric mould, milling

1. Introduction

Hot embossing is a relatively simple and flexible moulding technique which exploits the thermoplastic nature of materials to be imprinted. The replication step involves the plastic flow of the polymeric material into a mould that has a shape inverse of the desired part shape, which produces a negative copy of the mould patterns into the target polymer. The microstructured moulds are usually metallic and manufactured by a number of techniques [EDM, (UV)-LIGA, milling] which are time-consuming and costly.

In the recent years there has been a growing interest in using “plastic” moulds for most micro-moulding technologies, in particular for rapid and cost effective prototyping. These polymeric moulds were produced by a number of techniques such as:

- laser ablation of PSU, PEEK or PI that were used in photo-moulding/UV-Reaction Injection Moulding (RIM) [1] or hot-embossing and injection molding [2];
- photolithography in SU8\textsuperscript{®} for injection moulding [3];
- casting of epoxy “stamps” which were used for hot-embossing [4], [5] and UV embossing [6];
- casting of elastomeric (PDMS) moulds for hot embossing [7], [8];
- hot-embossing a higher temperature thermoplastic for subsequent replication in a thermoplastic of lower softening temperature; at the microscopic level polyether-ether-ketone (PEEK) proved successful for the hot-embossing into polymethylmethacrylate (PMMA) and polycarbonate (PC) [9] whereas nano-imprinted PC masters could be used for subsequent nano-imprinting into PMMA at room temperature [10].

2. Double hot-embossing process

Our approach uses a two-step replication process for hot embossing and exploits the glass transition of a thermoplastic polymer with high Tg, which is subsequently employed for imprinting another thermoplastic of lower Tg. So the same physical mechanism (glass transition of amorphous compounds and subsequent cooling) is exploited in both steps of the replication process, embossing of the polymeric replica mould and imprinting of the final plastic parts, hence its name “double hot-embossing”. Possible choices of thermoplasts for producing a rigid polymeric secondary mould are polymers with a high glass transition temperature such as polyimide, polyetherimide, or polysulfone, or PEEK. We chose polysulphone (PES) because its glass transition temperature was sufficiently higher than those of the polymers to be embossed like ABS, PMMA, PC, COC, so it was thermally stable at the processing temperatures. It also ensured an easy demoulding without release layer and was chemically compatible with our target polymers. Table 1 summarizes the thermal and mechanical properties of several thermoplasts.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Name & Polyimide & Polytetra-sulfone & Polysulfone & Polyether-etherketone \\
\hline
Formula & PI & PES (PESU) & PS & PEEK \\
\hline
Young’s modulus (GPa) & 1.3 - 4 & 2.3 - 2.8 & 2.5 - 2.7 & 3.5 - 3.9 \\
\hline
Glass transition temperature Tg (°C) & 250 - 340 & 210 - 230 & 187 - 190 & 140 - 145 \\
\hline
Linear thermal expansion coefficient (10^-5°C^-1) & 5.5 & 5.6 & 5.6 & 4.7 - 10.8 \\
\hline
Thermal conductivity (W/m.K) & 0.1 - 0.35 & 0.17 - 0.19 & 0.12 - 0.26 & 0.25 \\
\hline
\end{tabular}
\caption{Thermal and mechanical properties of several thermoplasts.}
\end{table}
Table 1: Thermal and mechanical characteristics of several thermoplasts [11].

<table>
<thead>
<tr>
<th>Name</th>
<th>Poly-etherimide (PEI)</th>
<th>Poly-carbonate (PC)</th>
<th>Polymethyl-methacrylate (PMMA)</th>
<th>Acrylonitride-Butadiene-Styrene (ABS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young's modulus (GPa)</td>
<td>3</td>
<td>2.1 - 2.5</td>
<td>2.5 - 3.5</td>
<td>1.79 - 3.2</td>
</tr>
<tr>
<td>Glass transition temperature Tg (°C)</td>
<td>215</td>
<td>150</td>
<td>90 - 110</td>
<td>90 - 102</td>
</tr>
<tr>
<td>Linear thermal expansion coefficient (10^-5°K^-1)</td>
<td>5 - 6</td>
<td>6 - 7</td>
<td>5 - 9</td>
<td>7 - 15</td>
</tr>
<tr>
<td>Thermal conductivity (W/m.K)</td>
<td>0.22 - 0.25</td>
<td>0.2</td>
<td>0.15 - 0.25</td>
<td>0.13 - 0.19</td>
</tr>
</tbody>
</table>

3. Applications

The double embossing process overcomes some geometrical limitations in mould fabrication such as those encountered in the case of microstructures in relief that for example are:

- bulk-micromachined in silicon,
- milled in a metallic substrate.

A master mould with a complementary shape easier to manufacture is thus produced and inverted during the first hot embossing step to yield a polymeric second generation mould with the correct shape. This feature was already exploited in with pyramids mechanically machined with shaped diamonds [9].

For instance, a 500µm high pyramid could not be produced as a boss with well defined corners in a (100) Si wafer using the strongly anisotropic chemical wet etching in KOH. Indeed, the pyramidal basis that might seem relatively large (500µm x 400µm) was already too small to allow for usual corner compensation to prevent convex corner undercut thus the etching of non {111} crystal planes. On the contrary, a deep pyramidal cavity of the same dimensions could be etched easily in the silicon master. Double hot-embossing was thus performed as illustrated in Fig. 1. The pyramid in relief was thus produced in PES, which was finally transferred into PMMA.

The rigid polymeric intermediate mould could be used for many imprinting cycles without apparent loss in pattern quality or perceptible differences in the final pattern transfer. The double hot-embossing therefore extended the applicability of silicon micromachining for cost-efficient manufacturing of microstructured moulds.

Another example where double hot embossing proved useful is for moulds manufactured by high precision mechanical machining [12]. The double hot embossing process is used here to manufacture a master mould in a more cost-effective manner.

The limitations come from the usual factors (precision of the machine; frequency of rotation of the spindel -cutting speed problematic), and specific factors (working mode of the tool: outer layer or shaped tool; strategic cutting method; roughness of the surface; material removal from the cavities; size of the tools).
In particular, grooves (Fig. 2-a) can be realized much more quickly (factor up to 10 in time, thus in cost) than ridges [Fig. 2-b and 2-c]. In the case of much narrower structures with higher aspect ratio, warping may occur when milling is performed without consolidation of the structure, as was the case for the 77 µm wide standing ridge presented in Fig. 2-c.

Fig. 2: Microstructures vertically milled in brass with a 500 µm end-mill tool using a KERN High Speed Precision Cutting 2525 machine fitted with a 35 000 rpm spindle: a) groove; b) 77 µm wide - 127 µm high ridge; c) 77 µm wide - 250µm high ridge.

The manufacture of a mould with a hemispherical boss and a smooth surface requires specifically designed shaped tools whereas the hollow negative shape can be produced much more easily using ball nose tools (Fig. 3). The surface geometry is at the image of the shaped tool and the surface state after cutting can be improved by reducing feed-rate and post-treatment (polishing, tribofinition).

Fig. 3: SEM cross-sectional view of a hemispherical cavity vertically machined with a ball nose tool: a) cross-sectional view (height: 170 µm; width: 150 µm); b) close-up view of the bottom.

In addition to prismatic machining, one of the great advantage of high precision machining lies in its ability to manufacture more complex surfaces (Fig. 4) such as NURBS surfaces (Non Uniform Rational B-Spline surfaces) which cannot be obtained using microelectronics-derived techniques.

Fig. 4: Example of NURBS surfaces (credits: www.3DVF.com)

We used here the double hot embossing process to make plastic parts with a complex shape that comprised two intersecting hemispheres with an optical finish and a hole in the middle. The challenges were numerous and consisted in manufacturing the hemispherical shapes, the intersections of the surfaces, the thinness of the walls, the hole with a complicated shape, and the surface finish. They prevented the manufacture of a mould with protuberant features. On the contrary, the negative shape with cavities could be produced in steel by high precision machining, EDM and polishing. The plastic parts with the right tone were therefore replicated in ABS using a PES mould which was itself hot-embossed with the steel mould (double inversion) as is shown in Fig. 5.

Fig. 5: Sequence of steps showing the double hot embossing process from an initial mould in steel to an intermediate mould in PES, to a final part in ABS; a) , b) and c) left: SEM micrographs of the steel master, PES intermediate mould, and final ABS part respectively; a) , b) and c): right 3D virtual images of the same.
A further advantage of the process comes from its potential for lowering the cost of the replication process as a whole, for prototyping and manufacturing both small and larger series. The fabrication of the polymer intermediate mould as a hot-embossed duplicate from the master mould is fast and low-cost. It can also prolong the life of the master mould in case of a brittle material like silicon, or when fragile fine microstructures in relief are being imprinted. In addition, several polymer moulds could also be used for running imprinting cycles in parallel.

Finally, the replication of moulds by hot embossing into polymeric duplicate moulds may offer an alternative to the rapid and low cost reproduction of metallic mould inserts using PDMS casting [13].

4. Conclusion

We developed a two-step replication process based on hot embossing using a rigid polymeric intermediate mould. We demonstrated the validity of the approach with a PES duplicate mould which was replicated into ABS and PMMA parts. This technique presents several advantages:

- it enables inverting twice a feature, which proves very useful when the manufacture of a negative mould is limited by the complexity and expense whereas a positive mould may be produced more easily and cost-effectively using the same shape as the part to be fabricated;
- it provides a fast and low-cost method for the production of second generation moulds, which can be exploited in prototyping or manufacturing.

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References